Answer Set Programming in a Nutshell

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Talk Outline

Introduction

- Answer Set Programming (ASP) is a recent problem solving approach
- The term was coined by Vladimir Lifschitz [1999,2002]
- Proposed by other people at about the same time, e.g. [Marek and Truszczyński, 1999],[Niemelä, 1999]
- It has roots in KR, logic programming, and nonmonotonic reasoning
- At an abstract level, relates to SAT solving and CSP.
- Book: [Baral, 2002]

Non-Monotonic Logic Programming

- "War of Semantics" in Logic Programming (1980/90ies):
  Meaning of programs like $a \leftarrow not\ b$, $b \leftarrow not\ a$?
- Great Schism: Single model vs. multiple model semantics
- To date:
  - *Well-Founded Semantics* [van Gelder *et al.*, 1991]
  - *Stable Model Semantics (aka Answer Set Semantics)* by Gelfond & Lifschitz [1988,1991].
- Shift in LP: *Answer Sets (=models)*, not proofs, *represent solutions*!
- Need techniques *to compute models* (not proofs)
- Concerted European-level effort:

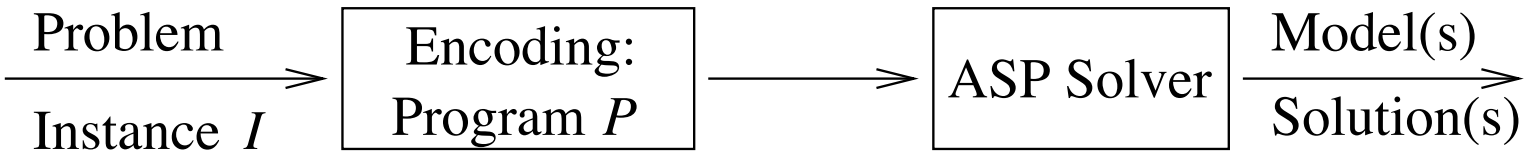
WASP

Working Group on Answer Set Programming,
IST-2001-37004, 2002-2005

ASP Paradigm

General idea: stable models are solutions!

Reduce solving a problem instance I to computing stable models of an LP



1. *Encode* I as a (non-monotonic) logic program P, such that solutions of I are represented by models of P
2. *Compute* some model M of P, using an ASP solver
3. *Extract* a solution for I from M.

Variant: Compute multiple models (for multiple / all solutions)

Nonmonotonic Logic Programs

- A *normal logic program* P is a (finite) set of rules of the form

$$a \leftarrow \ b_1, \ldots, b_m, not \ \ c_1, \ldots, not \ \ c_n$$

where all a, b_i, c_j are literals of the form p or $\neg p$, where p is a first-order atom from a (classical) FO signature.

In standard ASP, no function symbols are allowed;

  - "$\neg$" is called strong negation (also written as "$-$")
  - a may be missing (*constraint*, see later)

- In *disjunctive programs*, the rule head may be a disjunction $a_1 \vee \cdots \vee a_k$ of literals

- Notation: HB_P = set of all ground (variable-free) literals p and $-p$ with predicates and ground terms constructible from P.

Answer Sets

- The Answer Set semantics is based on 3-valued Herbrand Models (=consistent sets of ground literals $M \subseteq HB_P$), with incomplete information of the world
- For programs without "$-$," they are also called "stable models" and viewed 2-valued, with complete information of the world
- M satisfies a ground rule

$$a_1 \vee \cdots \vee a_k \leftarrow \ b_1, \ldots, b_m, not \ \ c_1, \ldots, not \ \ c_n \tag{1}$$

  if $\{b_1, \ldots, b_m\} \subseteq M$ and $M \cap \{c_1, \ldots, c_n\} = \emptyset$ implies $M \cap \{a_1, \ldots, a_k\} \neq \emptyset$.
- M satisfies ground program P, if M satisfies each $r \in P$.

Answer Sets (ctd.)

- **Key:** elimination of negation

Gelfond-Lifschitz (GL) reduct P^M

Given program P, remove from the grounding of P, $ground(P)$,

1. every rule of form (1) where some c_i is in M, and
2. all literals $not\ c_j$ from the remaining rules.

- M is an *answer set* of P iff M is a minimal model of P^M (wrt. $\subseteq$).
- Such M satisfies all rules, intuitively P justifies each atom in M.
- Note for non-disjunctive P, "a minimal" = "the least"
- Many equivalent definitions of answer set / stable model exist

Example

$$P = \{\ person(joey);$$
$$male(X) \vee female(X) \leftarrow person(X);$$
$$bachleor(X) \leftarrow male(X), not\ married(X)\ \}$$

- $M_1 = \{person(joey), male(joey), bachelor(joey)\}$ is stable
- $M_2 = \{person(joey), male(joey), married(joey)\}$ is not stable

In general, no, one, or multiple stable models exist.

Further stable model:

- $M_3 = \{person(joey), female(joey)\}$

Inconsistent Programs

- Consider the program

$$\{\ p \leftarrow not\ \ p.\ \}$$

- This program has NO answer sets
- Let P be a program and p be a new atom
- Adding

$$p \leftarrow not\ \ p.$$

to P "kills" all answer sets of P

Constraints

- Adding

$$p \leftarrow q_1, \ldots, q_m, not\ r_1, \ldots, not\ r_n, not\ p.$$

to P "kills" all answer sets of P that:

- contain $q_1, \ldots, q_m$, and
- do not contain $r_1, \ldots, r_n$

- Short:

Constraint

$$\leftarrow q_1, \ldots, q_m, not\ r_1, \ldots, not\ r_n.$$

Strong Negation

- Strong negation "$-$" is provided as possibility to express that something is provable false.
- This is different from negation as failure

Example

"At a railroad crossing, cross the rails if no train approaches."

$$walk \leftarrow at(L), crossing(L), not\ \ train\_approaches(L).$$

$$walk \leftarrow\ \ at(L), crossing(L), -train\_approaches(L).$$

- As for expressiveness "$-$" is easily compiled away; for every predicate p,
  - replace $-p$ by a fresh predicate $p_\neg$.
  - add the constraint $\leftarrow p(\vec{X}), p_\neg(\vec{X})$.

Exploiting Nondeterminism: Reviewer Selection

(1) $paper(p_1);\ paper(p_2);$
(2) $cand(\text{"}Thomas\text{"}, p_1);\ cand(\text{"}Enrico\text{"}, p_2);\ cand(\text{"}Marco\text{"}, p_2);$
(3) $assign(X, P) \leftarrow cand(X, P), not\ -assign(X, P);$
(4) $-assign(X, P) \vee -assign(Y, P) \leftarrow cand(Y, P), cand(X, P),\ X \neq Y;$
(5) $is\_assigned(P) \leftarrow assign(X, P);$
(6) $\leftarrow paper(P), not\ is\_assigned(P).$

Use disjunction in choice (3)+(4)

Answer sets:

$M_1 = \{\ldots, assign(\text{"}Thomas\text{"}, p_1), assign(\text{"}Enrico\text{"}, p_2), -assign(\text{"}Marco\text{"}, p_2)\};$

$M_2 = \{\ldots, assign(\text{"}Thomas\text{"}, p_1), assign(\text{"}Marco\text{"}, p_2), -assign(\text{"}Enrico\text{"}, p_2)\};$

Reviewer Selection: Cyclic Negation

(1) $paper(p_1);\ paper(p_2);$
(2) $cand(\text{"}Thomas\text{"}, p_1);\ cand(\text{"}Enrico\text{"}, p_2);\ cand(\text{"}Marco\text{"}, p_2);$
(3) $assign(X, P) \leftarrow cand(X, P), not\ -assign(X, P);$
(4) $-assign(Y, P) \leftarrow cand(Y, P), assign(X, P), X \neq Y;$
(5) $is\_assigned(P) \leftarrow assign(X, P);$
(6) $\leftarrow paper(P), not\ is\_assigned(P).$

(3)+(4): Choice of one element using unstratified rules (cyclic negation)

Answer sets:

$M_1 = \{\ldots, assign(\text{"}Thomas\text{"}, p_1), assign(\text{"}Enrico\text{"}, p_2), -assign(\text{"}Marco\text{"}, p_2)\};$

$M_2 = \{\ldots, assign(\text{"}Thomas\text{"}, p_1), assign(\text{"}Marco\text{"}, p_2), -assign(\text{"}Enrico\text{"}, p_2)\};$

Some Properties of Answer Sets

Minimality, Non-monotonicity

Every answer set M of P is a minimal model of P (wrt. $\subseteq$).

E.g. $P = \{a \leftarrow not\ \ b\}$: $M = \{a\}$ $P\cup = \{b \leftarrow\}$: $M = \{b\}$

Supportedness

Given an answer M of P, for every literal $a \in M$ there is some rule r from $ground(P)$ s.t. $M \models Body(r)$ and $M \cap Head(r) = \{a\}$.

But: stable $\neq$ minimal + supported! E.g. $P = \{a \leftarrow b;\ b \leftarrow a;\ a \leftarrow not\ \ a\}$

Generalization of Stratified Semantics:

If a normal P is "$-$"-free and "not " is layered ("P is stratified"), then P has a unique answer set, which coincides with the perfect model.

Failure of Cumulativity

From $a \in M$, for each answer set M of P, it does not follow that P and $P \cup \{\, a \leftarrow \ \}$ have the same answer sets (even if P has answer sets).

Computation / Complexity Issues

- For model computation, the following questions are of primary interest:

1. Computing some stable model of a given program P.
2. Computing all stable models of a given program P.
3. Given M and P, is M a stable model of P?
4. What search problems can be expressed by ASP?

- Following "classical" complexity theory, 1 and 2 have been reshaped as decision problems (does there exist some / yet another stable model)
- Problem 4 requires to resort to "nontraditional" complexity theory cf. [Marek and Remmel, 2003].
- Survey: [Dantsin *et al.*, 2001]

Basic Results

Theorem

Deciding whether a normal logic program P has some stable model is

- NP-complete in the propositional case;
- NEXPTIME-complete in the datalog (function-free) case;
- Σ_1^1-complete in the general first-order case.

- Similar results hold for deciding,
  - given P and a collection $\mathcal{C}$ of its stable models, whether P has some stable model $M \notin \mathcal{C}$;
  - given P and a ground atom a, whether $a \in M$ for some stable model M of P (brave reasoning)
- Cautious reasoning ($a \in M$ for *all* stable models of P) has complementary complexity.

Complexity: FO Logic Programs

Theorem

Deciding whether a normal logic program P with function-symbols has some stable model is Σ_1^1-complete.

Rough Sketch (for more, see [Schlipf, 1995]):

- Stable model existence of program P can be expressed by an existential second-order sentence Φ of form

$$\exists \mathbf{T} \forall \mathbf{x} \exists \mathbf{y} \phi(\mathbf{T}, \mathbf{x}, \mathbf{y}),$$

  where $\phi(\mathbf{T}, \mathbf{x}, \mathbf{y})$ is quantifier-free first order.
- Conversely, every Σ_1^1 sentence is equivalent to a sentence Φ of this form (by second-order Skolemization)
  Φ can be expressed (over the Herbrand universe) by stable model existence.

Complexity: FO Logic Programs /2

- Suppose wlog $\phi_i(\mathbf{T}\mathbf{x}, \mathbf{y}) = \bigvee_{i=1}^{n} \phi_i(\mathbf{T}, \mathbf{x}, \mathbf{y})$ is in DNF.
- Then, the program

$$
\begin{aligned}
T(\mathbf{x}) &\leftarrow not\ T'(\mathbf{x}) && \text{for each } T \in \mathbf{T} \\
T'(\mathbf{x}) &\leftarrow not\ T(\mathbf{x}) \\
sat(\mathbf{x}) &\leftarrow \phi_i^{\star}(\mathbf{T}, \mathbf{x}, \mathbf{y}) && \text{for each } i = 1, \ldots, n \\
sat(\mathbf{x}) &\leftarrow not\ sat(\mathbf{x}) \\
eq(x, x) &\leftarrow
\end{aligned}
$$

where $\phi^{\star}(\mathbf{T}, \mathbf{x}, \mathbf{y})$ is $\phi^{(}\mathbf{T}, \mathbf{x}, \mathbf{y})$ but

- "$\neg$" is replaced by "not", and
- "$=$" is replaced by "eq" (if present),

has some stable model iff Φ is true on its Herbrand universe.

Complexity of Disjunctive Stable Models

Theorem

Deciding whether a disjunctive logic program P has some stable model is

- Σ_2^p-complete in the propositional case;
- $\mathrm{NEXPTIME}^{\mathrm{NP}}$-complete in the datalog case;
- Σ_1^1-complete in the general first-order case.

- Note: no complexity increase in the full FO case (!)
- Disjunction can be compiled away:
  - Express stable model existence as $\exists \mathbf{M} \forall \mathbf{M}' \psi(\mathbf{M}, \mathbf{M}')$, where ψ is a Boolean combination of existential sentences.
  - rewrite to $\exists \mathbf{M} \forall \mathbf{x} \forall \mathbf{M}' \exists \mathbf{y} \psi'(\mathbf{M}, \mathbf{x}, \mathbf{M}', \mathbf{y})$, where ψ' is quantifier-free.
  - Emulate Arithmetic to express $\forall \mathbf{M}' \exists \mathbf{y} \psi'$ in FOL.

Expressiveness over Finite Structures

- Recall:

Fagin's Theorem

Over finite relational structures, $\Sigma_1^1 = \mathrm{NP}$

- Stable models have balanced expressiveness

Theorem

Over finite relational structures, stable model existence for

- normal logic programs $= \mathrm{NP}$ [Schlipf, 1995]
- disjunctive logic programs $= \Sigma_2^p$ [Eiter *et al.*, 1997a]

- Note: similar results hold for brave reasoning;
- For disjunctive logic programs, negation can be even restricted to equality and input relations!

ASP vs. Prolog

- **ASP features "pure" declarative programming**

  Under answer set semantics,

  - the order of program rules does not matter;
  - the order of subgoals in a rule does not matter;
  - termination is not an issue.

- **Nondeterminism in ASP:** Possibility to make guesses

- **But: function symbols are banned from standard ASP solvers**

  - Simple Horn LPs with function symbols are undecidable
  - Some decidable fragments: ω-restricted programs, finitary programs, finitely recursive programs, FDNC programs ...

    see e.g. [Baselice *et al.*, 2007], [Bonatti and Baselice, 2008], [Calimeri *et al.*, 2008] (DLV-complex), [Šimkus and Eiter, 2007]

Relationship to SAT

- Answer sets of a LP P are particular classical models of P
- Clarke aimed at characterizing the model of a (monotonic) normal program P by syntactic "completion" $Comp(P)$ [Clark, 1978]

Example

$P = \{p \leftarrow q\}$; $\quad Comp(P) = \{p \leftrightarrow q,\ q \leftrightarrow \bot\}$

- $Comp(P)$ captures the stable models of a normal LP P, if P is *tight* (= acyclic positive recursion in M).
- Does not hold in general

Example

$P = \{p \leftarrow q, q \leftarrow p\}$: $\quad Comp(P) = \{p \leftrightarrow q,\ q \leftrightarrow p\}$

$Comp(P)$ doesn't capture the single stable model $M = \{p, q\}$;

Note: P is not tight in M.

Relationship to SAT (ctd.)

- With additional *loop formulas* $LF(P)$, it is possible to capture the stable models [Lin and Zhao, 2002].

Stable models = completion + loop formulas

Intuitively, $LF(P)$ contains clauses enforcing that truth of atoms in a cycle must be supported from an atom outside.

Example (ctd.)

$P_1 = \{\ p \leftarrow q\ \}$: $LF(P_1) = \top$ $Comp(P_1) \cup LF(P_1) \equiv p \leftrightarrow q$

$P_2 = \{\ p \leftarrow q,\ q \leftarrow p\ \}$: $LF(P_2) = p \wedge q \supset \bot$ $Comp(P_2) \cup LF(P_2) \equiv \neg p \wedge \neg q$

- Also feasible for disjunctive programs + non-propositional program [Lee and Lifschitz, 2003], [Chen *et al.*, 2006].
- Based on this, some ASP solvers employ SAT solvers.
- Downside: exponentially many loop formulas in general

Relationship to SAT (ctd.)

- Benefits of ASP over SAT:
  - Transitive closure expressible
  - Express, to some extent. reasoning about multiple models
  - "high level",
  - predicates, rules, negation as failure, many constructs
- Comparisons of ASP/SAT Efficiency
  e.g., [Cadoli *et al.*, 2006], [Arieli *et al.*, 2004]
- Also relationship to / coupling with CSP has been explored
  e.g., [Baselice *et al.*, 2005]
- Some ASP systems (e.g. aspps) are strongly constraint driven.
- Constraints play an important role in model search

Relationship to Non-Classical/Non-montonic Logics

- **Nonmonotonic Logics:**
  Close relationship to other standard logics/formalisms in Nonmonotonic Reasoning (Autoepistemic Logic, Circumscription, Default Logic)

  Normal Logic Programs under Answer Set Semantics can be considered as a Fragment of Reiters Default Logic [Gelfond and Lifschitz, 1991]

- **McDermott-style Nonmonotonic Modal Logics**
  Close relationship to nonmonotonic Logic K45 [Marek and Truszczyński, 1993]

- **Equilibrium Logic** [Pearce, 2006],[Pearce and Valverde, 2006]
  Reconstruction of Answer Set Semantics in terms of the *Logic of Here and There*

Answer Set Solvers

- NP-/ Σ_2^p-completeness: Efficient computation of answer sets is not easy!
- Need to handle, for applications
  1. complex data (large data volumes)
  2. search
- Efforts to realize tractable fragments
- Many ASP solvers are available (function-free programs)

Approach:

- Logic programming and deductive database techniques (for 1.)
- SAT/Constraint Programming techniques for 2.

Different sophisticated algorithms have been developed
(like for SAT solving)

Answer Set Solvers

DLV	`http://www.dbai.tuwien.ac.at/proj/dlv/` *
Smodels	`http://www.tcs.hut.fi/Software/smodels/` **
GnT	`http://www.tcs.hut.fi/Software/gnt/`
Cmodels	`http://www.cs.utexas.edu/users/tag/cmodels/`
ASSAT	`http://assat.cs.ust.hk/`
NoMore(++)	`http://www.cs.uni-potsdam.de/~linke/nomore/`
Platypus	`http://www.cs.uni-potsdam.de/platypus/`
clasp	`http://www.cs.uni-potsdam.de/clasp/`
XASP	`http://xsb.sourceforge.net`, distributed with XSB v2.6
aspps	`http://www.cs.engr.uky.edu/ai/aspps/`
ccalc	`http://www.cs.utexas.edu/users/tag/cc/`

* + extensions, e.g. DLVEX, DLVHEX, DLV^{DB}, DLT, DLV-complex ** + Smodels_cc

- Several provide a number of extensions to the language described here.
- Answer Set Solver Implementation: see Niemelä's ICLP'04 tutorial.
- ASP Solver competition: see LPNMR 2007 conference;
- ASPARAGUS Benchmark platform `http://asparagus.cs.uni-potsdam.de/`

Architecture of ASP Solvers

Typically, a two level architecture

1. **Grounding Step:**
   Given a program P with variables, generate a (subset) of its grounding which has the same models

2. **Model Search**:
   More complicated than in SAT/CSP Solving:
   - Candidate generation (classical model)
   - model checking (stability!)
     - for SAT, model checking is in ALOGTIME
     - for normal programs, model checking is P-complete
     - for disjunctive programs, model checking is coNP-complete

Grounding Step

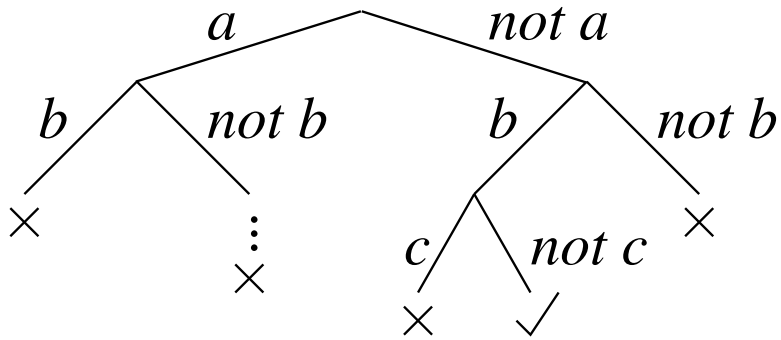
- Efficient grounding is at the heart of current systems
- Sophisticated techniques
  - DLV's grounder (built-in);
  - lparse (Smodels), gringo (clasp)
  - XASP, aspps
- Special techniques used:
  - "*Safe rules*" (DLV); every variable in a rule must occur on a unnegated atom in the body, whose predicate is not $=$ or any another built-in predicate
  - *domain-restriction* (Smodels)
- Problem: Grounding bottleneck [Eiter *et al.*, 2007]

  Research on nonground evaluation (e.g., You et al., Schaub et al.); XASP (XSB Extensions)

Model search

- Applied for ground programs.
- Different Techniques:
  - Translations to SAT (e.g. Cmodels, ASSAT)
  - tailored search procedures (Smodels, DLV, NoMore, aspps, clasp)

a :– *not* b.
b :– *not* a.
c :– *not* c, a.



  - Backtracking procedures for assigning truth value to atoms
  - Similar to DPPL algorithm for SAT
  - Important: Heuristics (which atom/rule to consider next); involved
- Stability check: unfounded sets, reductions to UNSAT

ASP Extensions

- Many extensions have been proposed, partly motivated by applications
- Some are syntactic sugar, other strictly add expressiveness
- Incomplete list:
  - nested expressions
  - cardinality constraints (Smodels)
  - optimization: weight constraints, *minimize* (Smodels); weak constraints (DLV)
  - aggregates (Smodels, DLV)
  - templates (for macros, DLT), external functions (DLVEX,DLVHEX)
  - Frame Logic syntax (for Semantic Web)
  - preferences: e.g., PLP, ordered programs
  - KR frontends (diagnosis, abduction, planning,...) in DLV
- Comprehensive survey of extensions (2005):

  `http://www.tcs.hut.fi/Research/Logic/wasp/wp3/`

Weak Constraints

- Allow the formalization of optimization problems in an easy and natural way.
- Constraints vs. weak constraints:
  - Constraints "kill" unwanted models;
  - Weak constraints express desiderata which should be satisfied, if possible.
- The answer sets of a program P with a set W of weak constraints are those answer sets of P which minimize the number of violated constraints.
- Such answer sets are called *optimal or best models of* (P, W).
- Other solvers feature similar constructs.

Guess-Check-Optimize Methodology

- Complements a natural "Guess & Check" Methodology
- Use weak constraints to filter out best (optimal) solutions
- Divide P into three main parts:

Guessing Part

$G \subseteq P$: The answer sets of $G \cup F_I$ represent "solution candidates" for instance I.

Checking Part (optional)

$C \subseteq P$: The answer sets of $G \cup C \cup F_I$ represent the admissible solutions of I.

Optimization Part (optional)

The optimization part $O \subseteq P$ consists of weak constraints, and defines an objective function $f : \mathit{Answer\_Sets}(G \cup C \cup F_I) \rightarrow \mathbb{N}$.
The answer sets minimizing f are selected.

Employee Assignment

- Goal: Divide employees in two project groups p_1 and p_2.
  1. Skills of group members should be different.
  2. Persons in the same group should not be married to each other.
  3. Members of a group should possibly know each other.
- Requirement 1) is more important than 2) and 3), which are equally important
- Layers [:x] express the relative importance of the requirements.
- ASP Solution (DLV) [Leone *et al.*, 2006]

```
assign(X,p1) v assign(X,p2) :-  employee(X).
:~ assign(X,P), assign(Y,P), same_skill(X,Y).    [:2]
:~ assign(X,P), assign(Y,P), married(X,Y).       [:1]
:~ assign(X,P), assign(Y,P), X!=Y, not know(X,Y).[:1]
```

ASP Applications

Problems in different domains, see

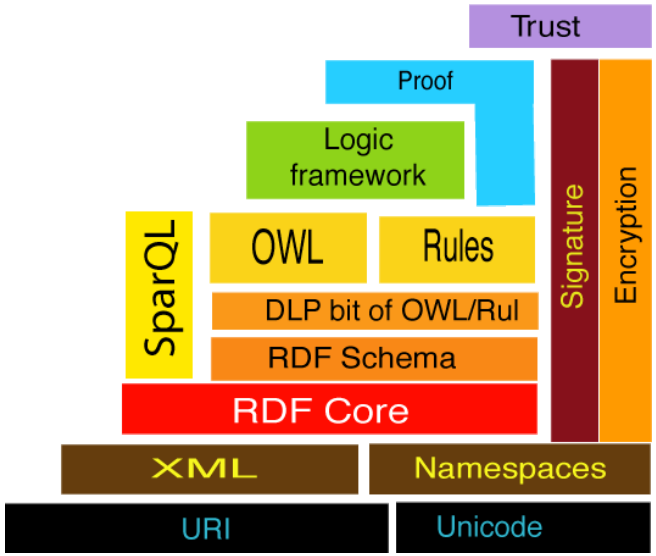
`http://www.kr.tuwien.ac.at/projects/WASP/report.html`

- information integration
- constraint satisfaction
- planning, routing
- diagnosis (e.g., Space shuttle reaction control [Nogueira *et al.*, 2001])
- security analysis
- configuration
- computer-aided verification
- biology / biomedicine
- knowledge management
- ...

ASP Front-Ends

- Some systems/groups offer *front-ends* for specific applications
- These frontends might be built-in or on top of an underlying ASP system
- DLV, e.g., offers a range of frontends
  - diagnosis
  - planning
  - inheritance reasoning
  - SQL3
  - ...
- Development of frontends for applications is a major research stream in ASP

ASP for the Semantic Web



- *RDF (Resource Description Framework)* is the SW data model
- RDF Schema enriches RDF by simple taxonomies and hierarchies
- More expressive: *OWL (Web Ontology Language)* which builds on Description Logics
- Rule languages: *Rule Interchange Format (RIF)* WG of W3C
- ASP in this context: see [Eiter, 2007]

ASP around Ontologies

- Different ways to exploit ASP and ASP techniques for ontologies:
  - **as a host language for ontology reasoning tasks**
    - Mapping / encoding of ontologies and DLs into ASP
    - Encoding of web query languages
  - **for (ad hoc) ontology management:** alignment, integration, merging, etc
  - **as a component for adding / integration rules with ontologies**
- Several extensions of ASP are geared towards this, e.g.,
  - Open Answer Set Programs [Heymans *et al.*, 2007]
  - Stable model theory for Rules on RDF/S: [Analyti *et al.*, 2005]
  - Nonmonotonic dl-programs / NLP-DL [Eiter *et al.*, 2008]
  - HEX programs /DLVHEX [Eiter *et al.*, 2005]
  - ONTODLP / ONTODLV [Calimeri *et al.*, 2003], [Ricca *et al.*, 2008]

Combining Rules and Ontologies

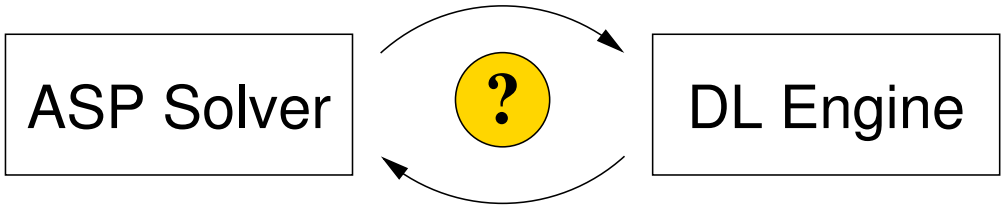
- Major Issue: Combining rules and ontologies (logic framework)
- ASP and ontology formalisms like RDF/s, OWL resp. Description Logics have related yet different underlying settings
- This makes combination non-trivial
- At the heart, the difference is between LP and Classical logic
- **Main Differences:**
  - Closed vs. Open World Assumption (CWA vs. OWA)
  - Negation as failure, strong negation vs. classical negation m
  - Unique names assumption (UNA), treatment of equality

supplier	branch	address
Barrilla	Roma	Piazza Espagna 1
Barilla	Milano	Via Cadorno 2
DeCecco	Roma	Via Salaria 10

Non-monotonic dl-Programs

- An extension of answer set programs with *queries to DL knowledge bases* (through dl-*atoms*) [Eiter *et al.*, 2008]
- dl-atoms allow to query a DL knowledge base differently

  bidirectional flow of information, with clean technical separation of DL engine and ASP solver ("loose coupling")



- Use dl-programs as "glue" for combining inferences on a DL base.
- System Prototype: NLP-DL
  `http://www.kr.tuwien.ac.at/research/systems/semweblp/`;
- ONTODLP/ONTODLV [Ricca *et al.*, 2008]: ASP + native ontologies + OWL interface

Data Integration

- Integrate data from local sources into global database, obeying local/global schema constraints [Lenzerini, 2002]
- Inconsistencies $\Rightarrow$ global database "Repairs" [Arenas *et al.*, 1999]:
- But: multiple repairs, query answering on them is quickly intractable
- Use ASP as an expressive formalism for *em repair specification and query answering* [Arenas *et al.*, 2000] etc.
- **Infomix** (IST-2002-33570; TU WIEN, U "La Sapienza", U Calabria, Rodan Systems): prototype system with ASP at the core [Leone *et al.*, 2005]
- Powerful information integration thanks ASP which similar systems (Hippo, ConQuer) could not host
  - can handle only limited schema constraints
  - have restrictions on queries (syntactic conditions)
- More discussion see [Eiter, 2005]

Workflow Management

- Execution management of orchestrated Web Services [Friedrich et al., 2008], in context of WS-DIAMOND (EU IST)

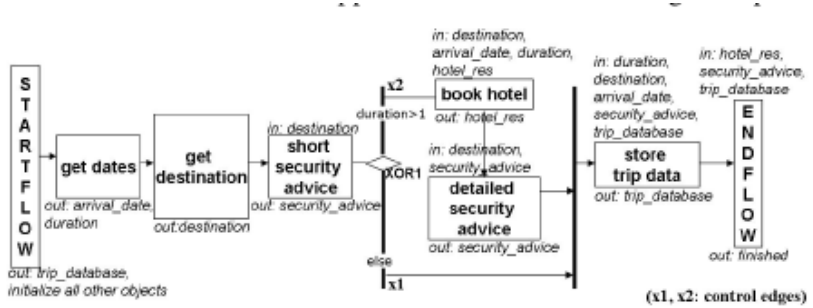


Figure 1. The trip planning example

- Problem: faulty action executions discovered; repair the workflow instance
  - **Input:** Work flow spec in WS-BPEL, exec log, faulty activities
  - **Output:** repair plan, taking contingencies into account
- Complex problem:
  - contingencies $\Rightarrow$ conditional planning
  - concurrency
  - transient errors, indeterministic actions

Workflow Management(ctd.)

- Friedrich et al. use ASP to compute repair plans
- different types of repair actions: re-execution (undo/redo), action substitution, compensation (undo)
- E.g., rules whether an activity is ok at a time point (=node in a tree):

$$
\begin{array}{ll}
-ok(A,T) & \texttt{if } failure(A,T). \\
-ok(A,T2) & \texttt{if } activity(A), -ok(A,T1), next(T1,T2), \\
 & \texttt{not } substituted(A,T2), \texttt{not } isTransFaulty(A,T1). \\
ok(A,T2) & \texttt{if } activity(A), node(T2), \texttt{not } -ok(A,T2).
\end{array}
$$

- Benefits of ASP:
  - readable specification
  - reasoning about time / time points
  - reason about dependencies (paths) in the control graph
  - inertia, default assumptions (exception handling)
- Prototype implementation in DLV: can handle medium sized orchestrated web services

Conclusion

- ASP is a recent problem sovling paradigm
- A body of theoretical work
- KR features, transitivity
- Many extensions & solvers
- Serves as a host formalism (good for prototyping)
- Assessment concerning applications:
  - N. Leone's LPNMR'07 talk

Research Topics

- Function symbols
- Program equivalence, optimization:

  E.g., *strong equivalence* [Lifschitz *et al.*, 2001] (many further notions [Woltran, 2008])

  $$P \equiv_s Q \text{ iff for all } R,\ P \cup R \text{ and } Q \cup R \text{ have the same answer sets}$$

- Proof systems (e.g., tableaux-based systems, [Gebser and Schaub, 2007], resolution [Bonatti, 2001])
- Modularity (e.g., [Janhunen *et al.*, 2007], [Eiter *et al.*, 1997b])
- Incremental model building (e.g., [Gebser *et al.*, 2008], [Calimeri *et al.*, 2007])
- Nonground ASP processing (e.g,. top down, You et al.; cf. XASP)
  Also magic sets [Faber *et al.*, 2008]), lazy grounding (e.g. Pontelli et al.)
- Debugging, software tools, methodology (e.g., [Brain *et al.*, 2007])

Expressing Disjunctive Stable Models in Σ_1^1

Rough Outline:

- Existence of a stable model is expressible by a second-order sentence

$$\exists \mathbf{M} \forall \mathbf{M}' \psi(\mathbf{M}, \mathbf{M}'), \tag{2}$$

  where $\mathbf{M}$, $\mathbf{M}'$ are lists of predicate variables and ψ is a first-order formula (in fact, a Boolean combination of existential sentences).

- This sentence can be rewritten to

$$\exists \mathbf{M} \forall \mathbf{x} \forall \mathbf{M}' \exists \mathbf{y} \psi'(\mathbf{M}, \mathbf{x}, \mathbf{M}', \mathbf{y}), \tag{3}$$

  where $\psi'(\mathbf{M}, \mathbf{x}, \mathbf{M}', \mathbf{y})$ is quantifier-free.

Lemma

Over arithmetic on the natural numbers $\mathcal{N}$ in a relational setting ($+$, $*$, exp are given by their graphs), formulas $\forall \mathbf{P} \exists \mathbf{z} \alpha(\mathbf{P}, \mathbf{z}, ...)$, where $\alpha(\mathbf{P}, \mathbf{z}, ...)$ is quantifier-free, are equivalent to first-order formulas.

Expressing Disjunctive Stable Models in Σ_1^1 (ctd.)

- We can emulate the natural numbers by a subset of the Herbrand universe, and conversely code the Herbrand universe (by Gödel numbering) to the natural numbers.
- Employing this, the formula

$$\forall \mathbf{M}' \exists \mathbf{y} \psi'(\mathbf{M}, \mathbf{x}, \mathbf{M}', \mathbf{y}) \tag{4}$$

  is (under this encoding) equivalent to a first-order formula $\alpha(\mathbf{M}, \mathbf{x})$.
- Plugging this into (3), we obtain a Σ_1^1 sentence

$$\exists \mathbf{M} \forall \mathbf{x} \alpha(\mathbf{M}, \mathbf{x}). \tag{5}$$

- The relations $+$, $*$, exp and the Gödel encoding can be provided with "guessed" predicates and first-order formulas.
- Hence, (2) is equivalent to a Σ_1^1 sentence

ASP vs Prolog: Greatest Common Divisor

Problem:

Compute the greatest common divisor of two integers $n, m > 0$

- Classical Method: Euclid's algorithm (DLV code):

$$
\begin{aligned}
gcd(X, X, X) &\leftarrow \#int(X), X > 1.\\
gcd(T, X, Y) &\leftarrow X < Y, gcd(T, X, Y1), Y = Y1 + X.\\
gcd(T, X, Y) &\leftarrow X > Y, gcd(T, X1, Y), X = X1 + Y.
\end{aligned}
$$

- Similar code in Prolog
- But: A genius like Euclid is *not* the average user

Question:

Natural encoding ?

Natural Greatest Common Divisor Encoding

ASP (DLV code):

% Declare when T divides a number N.
$divisor(T, N) \leftarrow \#int(T), \#int(N), \#int(M), N = T * M.$
% Declare common divisors

$cd(T, N1, N2) \leftarrow divisor(T, N1), divisor(T, N2).$
% Single out non-maximal common divisors T

$larger\_cd(T, N1, N2) \leftarrow cd(T, N1, N2), cd(T1, N1, N2), T < T1.$
% Apply double negation: take non non-maximal divisor

$gcd(T, N1, N2) \leftarrow cd(T, N1, N2), not\ \ larger\_cd(T, N1, N2).$

- Note: a stratified program, use of "double negation".
- A corresponding "natural" encoding in Prolog has to be more thoughtful!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